EFFECTIVE VENTILATION

9th AIVC Conference, Gent, Belgium
12-15 September, 1988

Paper 22

VENTILATION DESIGN FOR A BUS STATION

M. J. Holmes and T. Salusbury

Ove Arup and Partners
13 Fitzroy Street
London W1P 6BQ

SYNOPSIS

The paper presents the development of a ventilation scheme for a large bus station and passenger interchange in Bilbao, Spain. The main objective of the design was to ensure that pollution free conditions could be achieved within an enclosed waiting area that opened up on to, and was surrounded by, a semi-enclosed pick-up space, where there could be large number of buses with their engines running. Initial thoughts were to use natural ventilation, architectural and other constraints made this impossible so mechanical ventilation became necessary. The application of a multi-cell ventilation model to determine air movements within the whole station, including an assessment of the ability of the system to prevent exhaust fumes entering via open doors is described. This is followed by a discussion of the results of wind tunnel tests on a 1:400 scale model to determine pressure coefficients and likely pollutant levels in the semi-covered areas occupied by buses. The result of these studies was the presentation of the design scheme to the client, and we are looking forward to his response which should be available by the time of the Conference.

1. INTRODUCTION

The provision of comfortable conditions within a building is the everyday task of the building services engineer. There are occasions when circumstances make this more than routine. These occur when the conditioned space is so prestigious that no risks can be taken or conversely when there is little need to satisfy the usual demands for comfort but the space must still be acceptable for limited periods. In the first case published data can be used to specify design conditions' [1], and the appropriate plant designed and specified. The solution may be expensive but the design brief demands this approach. There is an intermediate field, a naturally ventilated and heated building, for example, where it is possible to predict the likely range comfort conditions, and so specify a failure rate. An approach to this design problem was described by Holmes [2] at the 6th AIC Conference. There is however, not much guidance available when designing on the 'edge' of comfort, that is perhaps for transitory space such as a waiting area. The occupants can be expected to be dressed for outside conditions, but clearly do not expect the waiting space to be quite like outside. The objective here is probably to aim for thermal conditions that will not cause serious complaints. How to assign a limit is rather more difficult. Accepting that tight control of the thermal environment is not the main objective, it is necessary to consider the quality of the air within the space. Perhaps this need not be of concern in a transitory region. Natural ventilation should suffice. If however, there are major pollutants in adjacent areas the problem becomes a little more interesting. In addition, if there are offices and restaurants nearby where clearly reasonable comfort standards are necessary the design is further complicated. This paper is concerned with that scenario.

The bus station described here is part of a major proposed redevelopment in the centre of Bilbao (located in the Viscaya region of North Spain), the Abando Passenger Interchange. The proposal evolved through the need for a new bus station and a rationalisation of the existing railway system along the river frontage in central Bilbao. The most suitable site was identified as the land at present occupied by the existing RENFE railway station and sidings Architects, Stirling Wiford and Associates were appointed as project architects to develop the project through concept to scheme stage (1:200), the stage where calculations of the type described in this paper are appropriate.

Ove Arup & Partners International Ltd were appointed in 1985 as consulting transportation, structural and building services engineers and were involved with the design of the project until July 1987 when their proposals were presented with those of the architect to the client, the Bizkaiko Foru Aldundia. The basic plan was the creation a new plaza in the centre of the site with pedestrian access from four arcades linking the new and old towns of Bilbao via a footbridge across the river (see Figure 1).

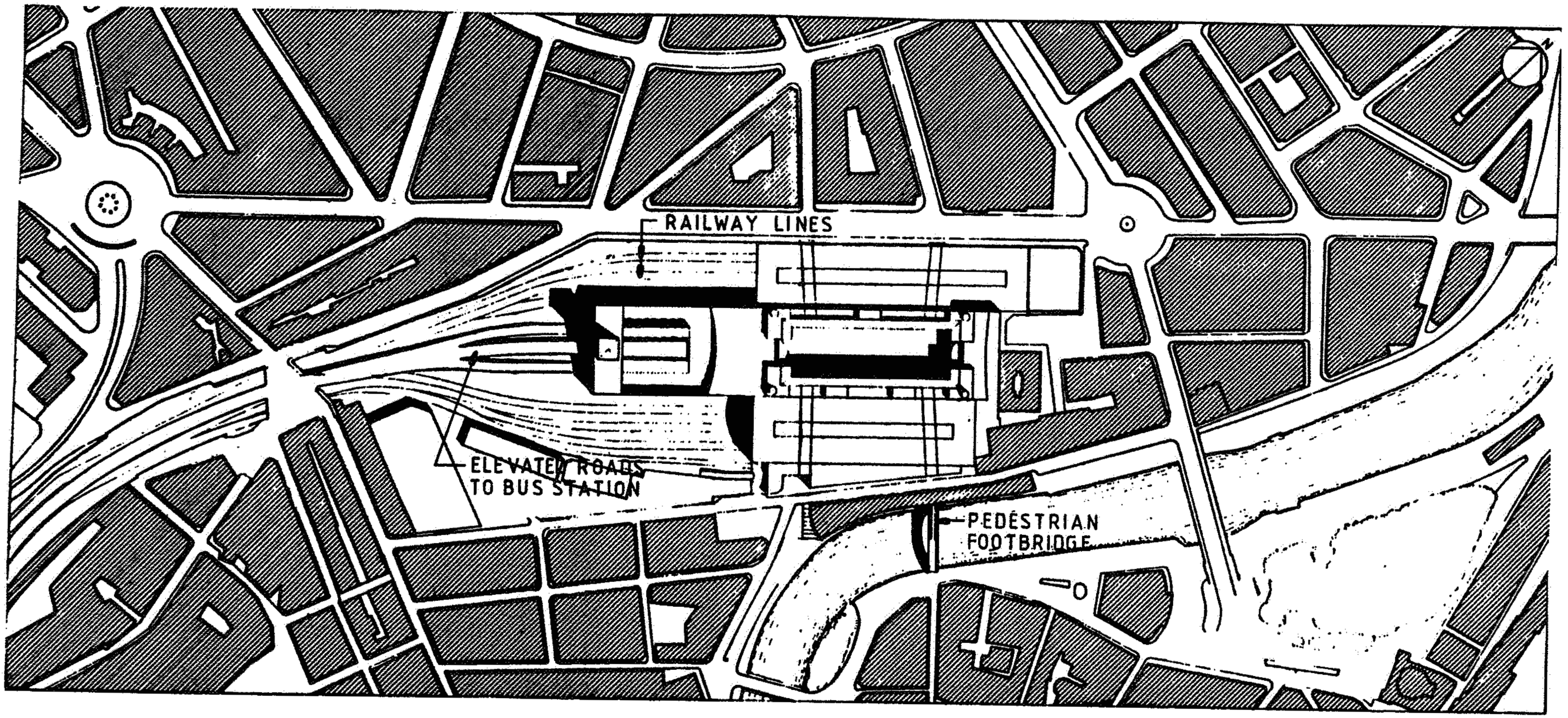


Figure 1 Overall view of the site

The entrances to the new bus station and railway station are situated at each end of the plaza with covered car/taxi drop-off points and 400 car parking spaces located in three basements, below the plaza. In addition, there is an underground service road around the perimeter of the basement car park for the delivery of parcels to the bus station and the general servicing of the plaza buildings. The interchange contains waiting, refreshment and administration areas, each of which has specific environmental requirements. It has already been suggested that special care needs to be taken when occupied areas are surrounded by pollutants. The approach employed for the design to scheme stage is described in this paper, which is in six main sections.

1. General description of bus station.
2. Design objectives - how the design conditions were specified.
3. Design Options - practical ways to achieve the design objective.
4. Analysis of the design - methods used to prove the design.
5. Description of the computer program.
6. Conclusions.

It is important to realise that design is a complex process and often iterative. That is, early decisions may have to be changed in the light of later studies, which could in turn affect the result of those studies. Because of this it is not possible to describe the evolution of the design without reference to what at the time would have been future work. In addition the paper is an attempt to describe what was done, and not to give an analysis of a large number of options, which in most cases are meaningless to the reader. It is also hoped that the paper demonstrates the practical use of ventilation theory

1.1 General description of the Bus Station

The proposed new bus terminus (Figure 1) comprises a suburban bus station at ground level and an external interurban bus station located above, on the roof of the suburban station. The bus station is flanked by railway tracks on each of its long sides. Access to the bus station is via an elevated roadway from which coaches pass up to the interurban bus station and local buses pass down to ground level and enter the suburban bus station on the short side opposite to that used by passengers entering from the plaza. These local buses pass around a covered roadway which is open on one side and surrounds the suburban passenger waiting concourse, Figure 2. There are twelve bus stands and passengers board and alight through three doors located between the roadway and the waiting area adjacent to each stand.

Figure 2 Section through the bus station

For the purpose of this paper the bus station can be idealized into the simple form shown in Figure 3. This comprises four main zones:

1. Entrance hall : volume 11320m^3 - Level 0m
2. Escalator well : volume 1080m^3 - Level 0m
3. Suburban concourse : volume 20,000m^3 - Level 7m
4. Interurban lounge : volume 9000m^3 - Level 14m

The levels referred to here are the height of the zones above an arbitrary datum. The main region of interest here is zone 3, the suburban concourse. This is connected to the interurban lounge above and the entrance hall below via the escalator well which forms an opening of 72m^2 at each of the two levels connecting the three spaces.

There are external doors at all three levels. The doors in the upper and lower levels are swinging doors, those in the concourse linking to each of the twelve bus stands are automatic sliding doors which remain closed except when in use. Each door has an area of 4.4m^2 with a crack length of 8.4m around it.

2. DESIGN OBJECTIVES

It has already been suggested that the designers main concern was the conditions in the suburban concourse. It is here where people could be subjected to unpleasant and even dangerous fumes from vehicle exhausts. It is also here where design conditions need to be carefully considered if energy consumption is to be optimized. The term optimized is chosen deliberately because minimum energy consumption would be achieved with all plant turned off. To optimize requires the best balance between heating and cooling to satisfy the local comfort requirements. In the present context it is necessary to consider three design objectives:

Acceptable level of pollutant
Winter Heating
Summer Cooling

2.1 Acceptable Level of Pollutants

The bus station is perhaps unique in that to perform its function it must necessarily be surrounded by its own pollutants. This means that while the local air is likely to be heavily polluted, the nature and level of the fumes should be quantifiable. This section considers both acceptable internal concentrations of the main pollutants and an assessment of local external levels due to diesel engines running while the buses are in the station. It is unlikely that the engines will be turned off because the average

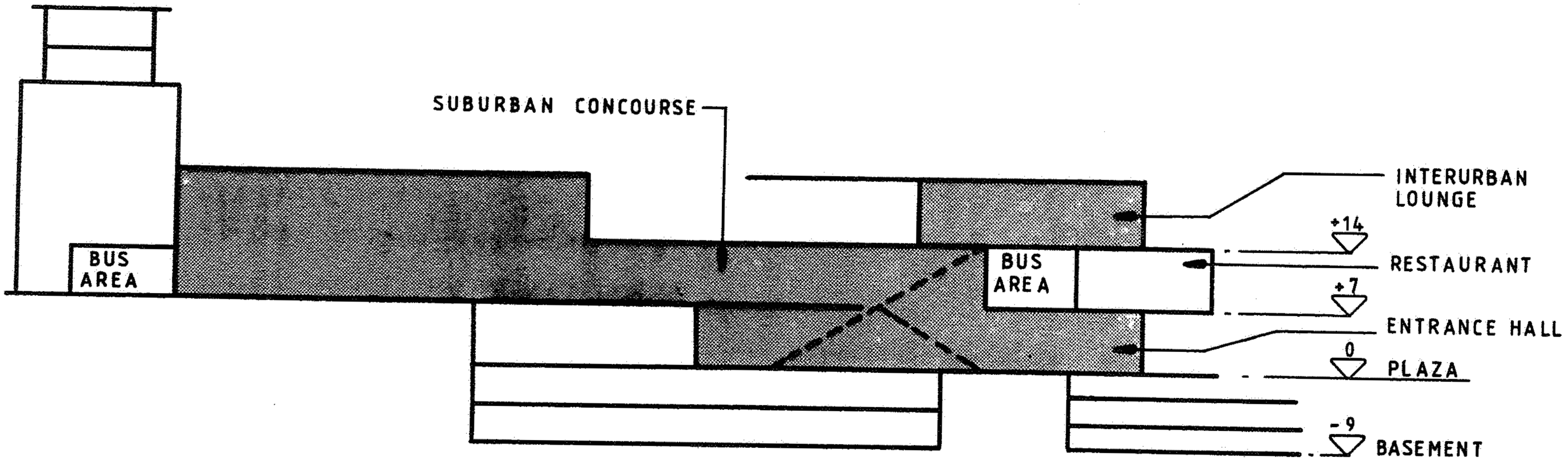


Figure 3 Simplified cross-section

predicted length of stay in the bus station is five minutes (local not long distance buses). They will generally be stationary with idling engines for four minutes of this period.

The design objectives here must be to assess the probable level of pollutant generation by the buses, together with that in the general locality and so determine the necessary dilution rate. The possibility of using a local extract system to remove the contaminants at source was considered but rejected because:

There is no standard position for bus exhausts.

Wind will have a significant influence on the trajectory of the exhaust gas jet.

Engine exhaust gas flows are hot (250°C at the engine when idling) and pulsating so again it is difficult to predict where the fumes will go.

So even if such a system had been adopted concourse ventilation would still have been an essential requirement to ensure safe conditions.

2.1.1 Acceptable Internal Concentrations

The major constituents of bus exhaust are shown in Table 2 together with recommended exposure limits[3,4].

Table 2: Threshold Limits

Pollutant	Exposures			
	10 minutes		8 hours	
	ppm	mg/m^3	ppm	mg/m^3
CO	400	440	50	55
NO	35	45	25	30
NO_2	5	9	3	5
Carbon	-	3.5	-	1.5

Both carbon monoxide and nitrogen monoxide react with blood haemoglobin which usually transports oxygen around the body. Nitrogen dioxide is a purgent red-brown gas which is both irritating and toxic. It reacts with water in the lungs to form nitric acid which reduces the lungs' ability to transport oxygen. Particulate matter can lead to the formation of scar tissues in the lungs and irritation of the eyes. The recommended [3,4] 8 hours and 10 minutes exposures to carbon black are 3.5 and $7.0mg/m^3$ respectively. However, reduced figures are used in Table 2. These can be qualitatively described as 'reduced visibility' and 'dense smoke'. Neither desirable but both apparently acceptable for the exposures quoted.

2.1.2 Assessment of Local Levels of Pollutants

Information on exhaust gas emission from diesel engines is generally quoted in parts per million of NO_x (ppm of combined oxides of nitrogen). The exposure levels quoted in Table 2 are different for the two oxides (NO, NO_2). It was therefore necessary to assume a ratio between the two. Ambient atmospheric levels of NO and NO_2 in towns are approximately equal [5] but peak levels are in the ratio 2:1. Under full load, a diesel engine produces rather less NO_2 [6], however, as previously stated, buses will be idling for most of their stay a ratio of NO:NO_2 of 70% : 30% was assumed for the calculation of air change rate.

To obtain the generation rate of the pollutants it was first necessary to obtain exhaust volumes flow rates for diesel engines and then relate this to the content of the gases. Typical figures [7,8] are given in Tables 3 and 4, where for the purpose of design a typical engine has been assumed to have a capacity of 8 litres.

Table 3: Exhaust Flow Rates

Engine Condition		Exhaust flow rate (m^3/h)		
Load	Speed (rpm)	6 litre	8 Litre	10 Litre
Idling	320	57.6	76.8	96.0
Full Load	800	144.0	192.0	240.0

Table 4: Exhaust Constituants

Engine Condition Load	Speed (rpm)	Emission by volume (ppm)		Volume of Pollutant (m^3/hr)	
		CO	NOX	CO	NO_x
Idling	320	510	190	0.039	0.015
Full Load	800	2130	2170	0.409	0.417

Diesel smoke is difficult to quantify. The usual measure for particulate carbon (C) is Dmg/m^3 (milligrams of standard diesel smoke per cubic metre of air). This measure is actually less than the total solid content in the air because the larger, heavy, particles contribute little to the obscuring effect of the smoke. In practise these particles may settle out, although with exhaust gas temperatures of 250°C at the engine most of the gaseous pollutants tend to rise.

As in the case of the oxides of nitrogen it was necessary to make a design assumption. A 10 tonne vehicle travelling at 10km/hour up a 2% gradient can generate as much as 25,000mg/hour of particulate material [9]. Stationery buses are unlikely to generate as much and because the of tendency of heavier particles to settle a reduced figure of 12,000Dmg/m³ was taken for the ventilation calculation.

2.1.3 Air Quantities Required to Dilute the Pollutants

A safe design criteria would be to assume that all the pollutants emitted by the buses enter the concourse area. It was however also thought necessary to consider conditions in the covered loading area around the concourse (Figure 2). The amount of 'fresh' air required to obtain acceptable conditions in the concourse depends upon the contaminant level of that air, the number of buses at the station as well as the content of the exhaust. Typical levels of ambient CO, NO, NO_2 and C are given in Table 5 [5].

Table 5: Ambient Pollutant Levels

Pollutant	Level	
	ppm	mg/m³
CO	10.0	11.5
NO	0.9	1.0
NO_2	0.3	0.5
C	-	0.5

The frequency of traffic was the subject of a study by Arup Traffic Engineering, this is not included in the present paper. The results were a daily flow of 600 buses with a peak hour flow of 50 in the evening.

The data contained in Table 5, in conjunction with the assumed exhaust emissions (Table 4), was used to determine the amount of 'fresh' air necessary to dilute each of the pollutants to 'safe' levels (Table 6), and then converted to air change rates for different patterns of use, (Table 7).

Table 6 Dilution flow rates (m^3/hr)

	CO	NO_X	C
8 hour exposure			
Idling	975	1852	12000
Full Load	10225	51482	12000
10 minute exposure			
Idling	100	1064	4000
Full Load	1049	29575	4000

Table 7 Required air change rates

Condition	Pollutant			Exposure
	CO	NO_X	C	
Constant idling	0.82	1.55	10.00	8 hour
	0.09	0.87	3.33	10 mins
Peak, 50 buses per hour	0.44	1.81	1.85	10 mins
Peak 5 minutes (12 buses)	0.13	3.01	1.78	10 mins

These air change rates (Table 7) are based on a ventilation efficiency of 100%. Something near that figure could be achieved with a well designed air distribution system and is therefore a reasonable assumption for the concourse. In addition not only are the pollutant emissions an overestimate (in particular that for particulate carbon from an idling engine) but not all the fumes can be expected to enter the concourse. Ventilation efficiency for the semi-open bus waiting area surrounding the concourse will depend upon local conditions. An efficiency of 50% would probably not be too pessimistic.

The design air change rate for the concourse and surrounding were therefore taken as 3 and 6 air changes respectively.

It must be said here that the concept of an air changes rate for what is a fairly open area might be thought a fairly novel idea. It was however, necessary to have a quantitative method to assess the level of pollutant that might enter the concourse area. A notional air change satisfies this requirement, and is later used in the interpretation of the wind tunnel tests.

2.2 Winter Heating

In this case only problem is to assess the probable activity and clothing levels of the occupants. It was thought reasonable to assume that they would have walked several hundred metres before arriving at the waiting area and that they would be dressed for outside conditions. In addition, fairly still air conditions would be expected. A comfort analysis according to Fanger's [1] theory for active people ($123w/m^2$) with a clothing level corresponding to 1.5 clo, suggested that 12°C would be a suitable design temperature would appear to be 12°C.

Because of the need to use relatively large amounts of air ($20m^3/s$), to minimise the entry of contaminants, a warm air system was considered to be appropriate (otherwise a radiant system would have been appropriate). It is worth mentioning here that with a peak occupancy of 275 people the application of current regulations [10] would result in a fresh air requirement of $3.3m^3/s$ (0.6 air-changes).

The large amounts of air required suggest that some of exhaust air heat recovery system should be considered. The low internal winter design temperature means that such a scheme is unlikely to be cost effective. It could be argued that higher design temperatures could then be used without any increase in energy consumption. If this were done then the occupants level of clothing would not be compatible with local environment. Alternatively some recirculation could be used (and this is included in the proposed design) provided the level of contaminants does not become unacceptable.

2.3 Summer Conditions

The main source of heat gain are people and lights, with a solar contribution from a skylight in the centre of the concourse. The space has high thermal inertia and a well insulated roof. It was therefore felt that mechanical ventilation would be adequate perhaps with night time pre-cooling. This fits in well with the ventilation demands for the dilution of pollutants.

3. DESIGN OPTIONS

Section 2 went slightly beyond the general design objectives by including an assessment of the amount of air required to dilute exhaust emissions to acceptable levels. This section presents the options open to the designer to achieve those objectives. Analysis of the proposed design is covered in Section 4.

The range of options that were considered are given below in order of increasing cost, complexity and environmental comfort:

1) Treat the suburban bus station as an external covered naturally ventilated space with columns supporting the deck of the interurban bus station above. There would need to be doors to the escalators serving the interurban lounge above and the entrance hall below. This is the only solution which would enable natural ventilation throughout.

2) Introduce a small central area for the cafe facilities and toilets with people waiting 'outside' in the same space as the buses. This central core, however, reduces the effectiveness of natural cross flow ventilation.

Both (1) and (2) above were in conflict with the architectural concept and were therefore not considered to be viable technical solutions.

3) Accept the architects proposed scheme with an internal occupied, environmentally controlled space, with buses outside. The bus occupied area could be partially screened off at low level also.

4) The most sophisticated solution would be to utilise a separate ventilation system for the concourse area and the bus area. The external ventilation system would consist of a local extract system at each bus parking bay. This would limit future flexibility as the extract would need to be close to the exhaust pipe to be effective. The difficulties associated with the implementation of a local extract system (see 2.1), in conjunction with an anticipated high life cycle cost of the proposal resulted in the recommendation not to adopt this method.

It was felt that the proposed architectural solution is analogous to an airport arrivals/departure lounge rather than an external covered garage and hence option 3 above was studied in more detail (Section 4) in order to quantify the major design parameters. In particular, the possibility of pressurizing the suburban concourse was examined using the mechanical ventilation system to minimise the entry of bus fumes. This was considered to be of particular importance as the concourse is completely surrounded by bus stands.

4. ANALYSIS OF THE DESIGN

For the purpose of this paper this means the ventilation strategy. The sole objective of the analysis was to prove that the quality of air within the concourse would be both acceptable to those waiting for buses and, of course, offer no danger to their health. To do this it was necessary to ensure an adequate supply of fresh air to the concourse.

This can be done by carrying out an analysis of air movements within and into the areas of interest. Such an analysis can done by means of a multi-cell ventilation model. The main problem with using such a model (excluding its validity) is in the specification of the local wind climate. This can be done by a wind tunnel test. In this case such tests were considered essential to determine the probability of obtaining satisfactory conditions. A by-product of such tests would be the most satisfactory position for the fresh air inlets.

Wind tunnel tests are expensive and it takes some time to construct a model and do the test. It was therefore thought necessary to make a preliminary analysis of airflow patterns within the building using a multi-cell ventilation model. This analysis would give a good idea of what to look for in the wind tunnel test programme. This section first describes that analysis and then the wind tunnel tests.

4.1 Ventilation Analysis

The bulk of the work described here was done using the Arup Environmental Prediction Units' computer program VENT. This program, which was also used for the analysis of the Gateway 2 building [2], is described in Section 5 of this paper. It is sufficient to state here that in addition to the usual consideration of flow through orifices and cracks VENT contains analytical routines to allow the simultaneous calculation of inflow and outflow at large openings such as the bus station doors.

4.1.1 Scope of the Analysis

With the exclusion of a local exhaust extract system there are only two ways to ensure adequate ventilation:

a) Mechanical ventilation by pressurisation of the concourse.
b) Natural ventilation.

Mechanical ventilation involves pressurising the concourse by supplying air either to the concourse itself or to the two main linked spaces. This has the advantages of flexibility, reliability and ease of control.

Natural ventilation can take place as a result of both wind and thermal effects. The thermal or "stack" effect is usually negligible compared with that of the wind as the pressure differences induced by thermal changes in air density are much smaller than those due to the wind. The size of the concourse area makes it unlikely that an effective cross flow could be achieved. In addition, simple calculation demonstrated that an adequate level of ventilation would achieved at the most 50% of the time. This was done by assuming an effective pressure coefficient over the building of 0.5, two doors ($6.6m^2$, each) open on each side, and the exhaust from two buses. The wind speed exceeded for 50% of the time was taken as 4.5m/s, so following the CIBSE Guide [9]:

$$Q = 0.827 \times \frac{A}{\sqrt{2}} \times \Delta p \qquad (1)$$

Q is the volume flow rate.

A is the area of two doors

Δp is the pressure drop across the building (= 6Pa).

Thus the ventilation air flow that will be exceeded 50% of the time is approximately 19 m^3/s. The exhaust from two buses would require about $16m^3/s$ to dilute it to a safe level. Natural ventilation was therefore not thought to be acceptable.

The study was therefore confined to an investigation of mechanical ventilation. The amount of air required to dilute the exhaust to an acceptable level has already been shown to be about $30m^3/s$. Supplying all this air with the doors closed could generate large pressure within the concourse. The simplest way to prevent this happening is to add leakage. The size of a suitable relief duct - which remains open all the time - formed part of the studies.

4.1.1.1 Building Geometry

The simplified version of the building in Figure 3, was used for all the analytical work.

There are external openings from the concourse in the form of doors and small natural leakage paths such as cracks around doors. Each bus stand has three doors which open to enable boarding from and alighting to the concourse.

There are also doors and cracks in the urban lounge and ticket areas. Although the bulk of the study was concerned with leakage through large open doorways, the leakage through closed doors can be significant when pressurized to 50pa. One manufacturer of sliding doors gives a figure that result in a leakage from all 12 doors of $1.5m^3/s$, whereas a 3mm crack would result in between 7 and $8m^3/s$. The ANSI/ASHRAE/IES 90A-1980 air leakage standard for non-residential dwellings, swing, revolving or sliding doors gives $4.5m^3/s$. This has been taken here to be typical of what might occur.

The following assumptions were made regarding the geometry of the building:

a) Both the urban lounge and the entrance hall are linked to the concourse through openings of $72m^2$ area.

b) The doors in the urban lounge and ticket hall are swinging doors. Those in the concourse are automatic, sliding doors which remain closed except when in use. The details of the doors and the way in which they are used are important to determine the leakage paths out of the building and also the rate at which pressure builds up after they are closed.

4.1.1.2 Input parameters

The major factors influencing air-flow in the concourse were each investigated and their relative importance examined. This was done by taking the following simple 'control' case:

a) No wind

b) Summer temperatures 29°C outside, 20°C inside (these are assumed design conditions that exaggerate the effect at the large doors)

c) Mechanical ventilation rate of $25m^3/s$, supplied via systems in the urban lounge and entrance hall

d) Four open doors in the concourse.

Any study of this nature will have the potential for a very large number of computer runs, Figure 4 shows the total number of combinations of all variables that might have been considered with air supplied to linked spaces only. The figure also shows which combinations were considered significant for the purpose of analysis.

After an assessment of these preliminary runs further cases were considered investigating the effects of recirculating some air in linked spaces, supplying some air to the concourse and to determine the size of the relief duct. The supply air volumes chosen in these further cases were based on the normal ventilation requirements for all three spaces. The relief duct area was chosen to maintain a positive pressure in the concourse.

4.1.1.3 Output Evaluation

A summary of all the computer runs (tests) is given in Table 8, with some selected results given diagrammatically in Figure 5 Obviously the amount of air which enters the concourse depends on the internal pressure and the air temperature, as these determine the level of the neutral plane, i.e. the level at which internal and external pressures are the same for any opening.

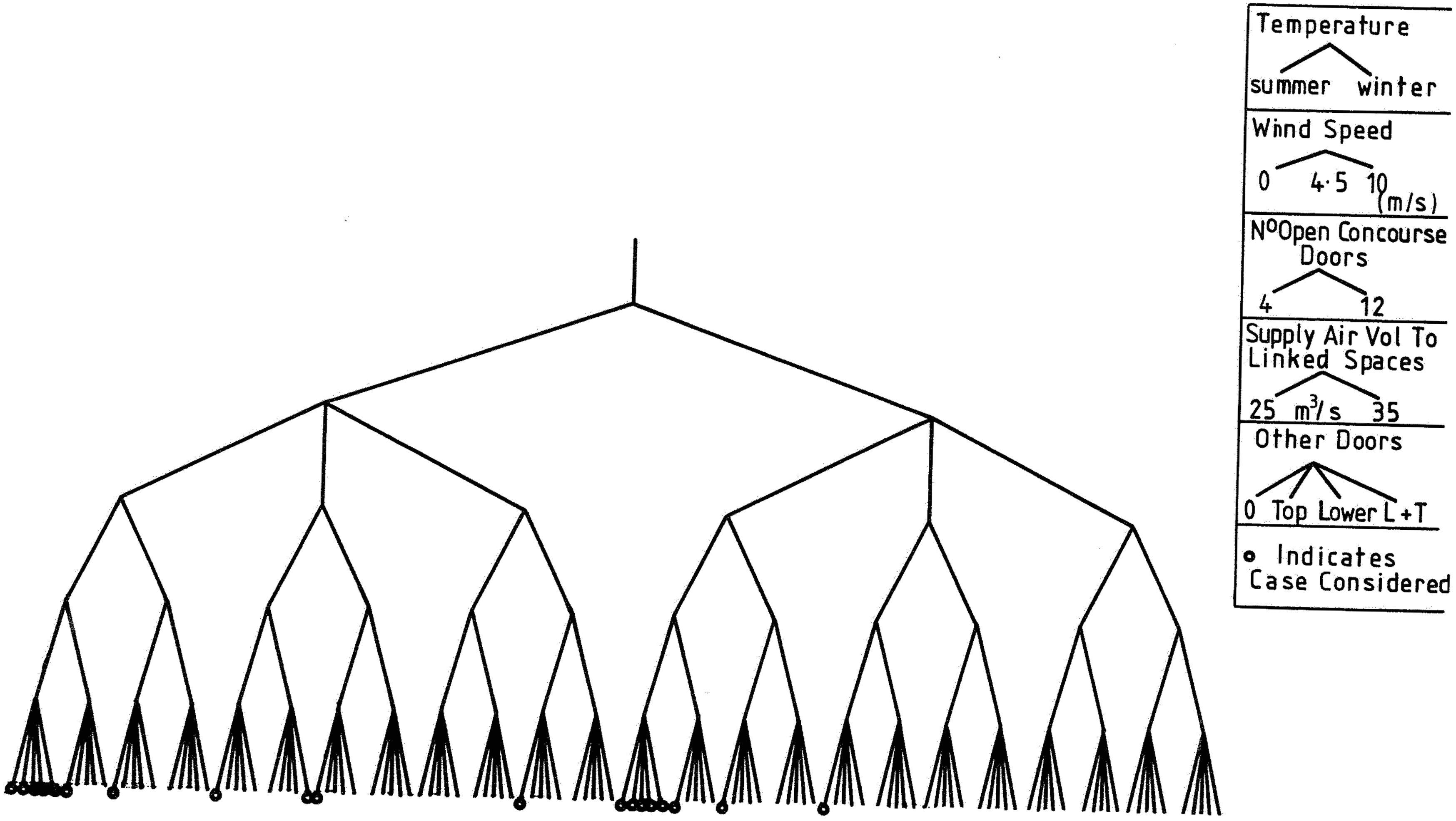


Figure 4 Possible combinations for analysis

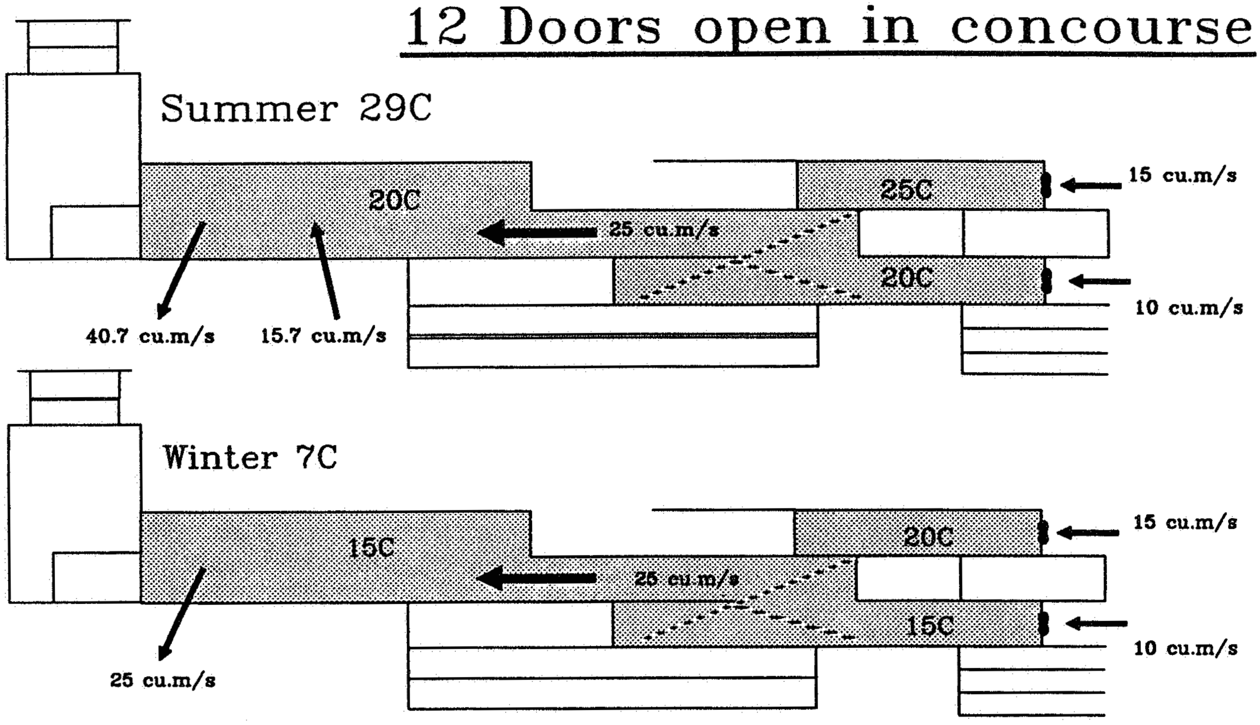
Table 8a: Results with air only supplied to rooms adjacent to the concourse

Wind (m/s)	Temperature (°C)	Total Supply Vol. to all spaces	Concourse doors open	Other doors open	Concourse Pressure above ext at +7m (Pa)	Incoming air through external doors to concourse (m^3/s)	Supply air to concourse from linked spaces (m^3/s)	Total concourse air change rate
0	29	25	4	0	0.74	0.04	15	4.5
0	29	35	4	0	1.41	0	35	6.3
0	29	25	12	0	0.49	15.7	25	7.3
0	7	25	4	0	0.92	0	25	4.5
0	7	35	4	0	1.62	0	25	6.3
0	7	25	12	0	0.27	0	35	4.5
0	29	25	4	1, Room 1	0.93	0.9	25	3.8
0	29	25	4	1, Room 4	1.03	0.0	20.5	5.3
0	29	25	4	1 each Rooms 1&4	0.63	1.3	29.3	3.7
0	7	25	4	1, Room 1	1.02	0	19.1	4.9
0	7	25	4	1, Room 4	0.52	0	27	3.0
0	7	25	4	1 each Rooms 1&4	0.92	0	16.7	4.5
0	29	25	2	0	2.9	0	25	4.5
4.5	29	25	4 (2+2)	0	4.69	13.2	25	6.9
4.5	29	25	4 (4 wind)	0	6.27	0.06	25	4.5
4.5	7	25	4 (2+2)	0	4.96	13.5	25	6.9
4.5	7	25	4 (4 wind)	0	6.94	0	25	4.5
4.5	29	25	4 (4 lee)	0	1.38	0.07	25	4.5
4.5	7	25	4 (4 lee)	0	1.23	0.01	25	4.5
4.5	29	0	4 (2+2)	0	0.3	28.5	0	5.1
10.0	29	25	4 (2+2)	0	4.69	13.2	25	6.9
10.0	29	25	12	0	- 0.53	71.8	25	17.4
0	29	35	4 (2+2)	1 each Rooms 1&4	0.93	0	28.4	5.1

Table 8b: Results with air supplied to all rooms

Wind	Temperature (°C)	Supply Vol. (m^3/s) Room 1	Room 3	Room 4	Concourse doors open	Vent area/m^2	Other doors open	Concourse Pressure (Pa)	Incoming air through external doors (m^3/s)	Total Supply to concourse to concourse (m^3/s)	Total concourse air change rate
0	29	10	10	15	4	0	0	1.41	0	35	6.3
4.5	29	10	10	15	4 (2+2)	0	1 each Rooms 1&4	4.74	13.79	24.5	4.4
0	29	10	20	15	0	12	1 Room 4	17.53	0	35.4	6.4
0	29	6.5	17	6.5	0	12	1 Room 1	9.55	0	21.6	3.9
0	29	7.5	17	7.5	0	12	1 Room 1	10.32	0	23.3	4.9
0	29	8.5	17	8.5	0	12	1 Room 1	11.16	0	25.0	4.5
0	29	9.0	17	9.0	0	12	1 Room 1	11.59	0	25.8	4.6
0	29	9.5	17	9.5	0	12	1 Room 1	12.04	0	26.7	4.8
0	29	9.5	17	9.5	0	12	1 Room 1	12.82	0	28.1	5.1
0	29	9.5	17	9.5	0	12	1 Room 1	9.83	0	28.4	5.1
0	29	9.5	17	9.0	0	12	1 Room 1	12.59	0	27.7	5.0
0	29	9.5	17	8.5	0	12	1 Room 1	12.36	0	27.3	4.9
0	29	5.0	17	7.5	0	5	1 Room 1	22.25	0	17.4	3.1
0	29	5.0	17	7.5	0	5	2 each Rooms 1&2	6.50 23.93	0	17.0	3.1
0	29	5.0	17	7.5	0	5	1 Room 4		0	18.1	3.3

12 Doors open in concourse



4 Doors open in concourse

also doors open in adjacent spaces

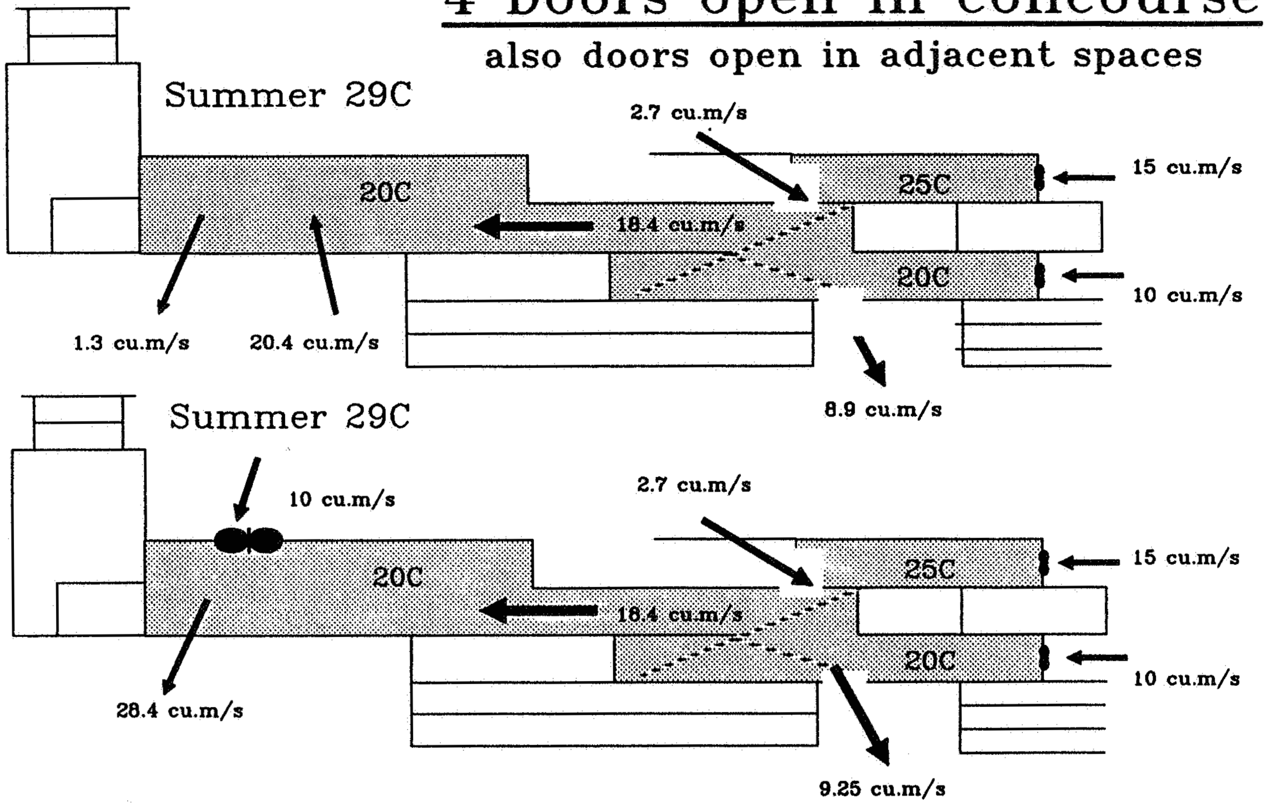


Figure 5 Predicted airflow patterns

The internal pressure depends on the effective area through which air can escape, and the supply volume. Increasing the number of concourse doors which are open increases the effective outlet area and therefore reduces the pressure. Even in still air this increases the volume of air entering from outside. For instance, when two doors are open there is no incoming air, when four doors are open $0.04m^3/s$ of air enters the concourse. If all twelve doors are open the ingress of air is $15.7m^3/s$.

The effect of wind overrides all other effects by inducing large pressure differences across the doorways. Under these circumstances it is not possible to prevent air coming in to the concourse, by pressurising the concourse as the volume of supply air required would be too great. However, it is possible to dilute any pollutants that enter to an acceptable level. The degree of pressurization obviously depends upon the amount of air supplied to the concourse. This can be increased directly by altering the supply air flow in that area, or indirectly by air from adjacent spaces. Inward air flow occurs only as a result of stack effect and is usually insignificant, outward air flow occurs because open door provides a low resistance to flow. This means that a fairly large proportion of air supplied to the linked spaces will not be useful in ventilating the concourse. The results given (Table 8) are for one open door only in linked spaces, doubling the open area will make the outward airflow from linked spaces more significant.

The open area required for a relief duct was $5m^2$, given a supply volume of $29.5m^3/s$ and a maximum allowable pressure across it of 50Pa.

Altering the volumes of extract, and hence the degree of pressurisation of the urban lounge and entrance hall has very little effect on flow inside the concourse. As the degree of pressurisation is reduced, some air flows from the escalator well to the entrance hall and urban lounge, but there is no flow from the concourse to the escalator well. This means that polluted air should not spread out of the concourse area.

4.1.2 Conclusion and recommendations

The computer studies resulted in the recommendation the following ventilation rates:

a) $17m^3/s$ supply air to concourse,

b) $15m^3/s$ supply air to urban lounge,

c) $10m^3/s$ supply air to ticket hall,

d) Half of the air supplied to the entrance hall and urban lounge can be extracted and some of it can be recirculated.

These ventilation rates would maintain an air supply to the concourse of 20m^3/s. The extra air must be supplied because air supplied to the linked spaces can escape through any open doors in these spaces and cannot therefore be used to ventilate the concourse.

The ventilation rates are based on the requirement to dilute exhaust pollutants in all three spaces at both peak and average times. In addition these supply air quantities should satisfy fresh air requirements, air movement criteria and limit the concourse temperature to 5°C above the ambient external temperature.

The initial studies also suggested that it would also be possible to pressurise the concourse by supplying air at 20m^3/s to the entrance hall and at 15m^3/s to the urban lounge only. It is however, necessary to ventilate and supply fresh air to all the spaces.

On windy days some fumes will enter the concourse but the supply rate is sufficient to dilute any fumes which do enter to an acceptable level. In addition, under these conditions the concentration of fumes present in the bus-occupied areas will be lower.

Pressure within the concourse must not be allowed to rise above 50Pa above atmospheric as this makes it difficult to open and close doors. The pressure will only rise to this level if all the doors are closed, and can be limited by a relief duct with an open area 5m^2 at roof level. This could be achieved by opening a window in the roof light during the summer. It might also be possible to recirculate some air or recover some heat from the outgoing air during the if a separate duct is provided.

The design of the proposed mechanical ventilation system cannot be carried out in detail without an analysis of the unsteady state. The variation of pressure with time and the time taken to establish a steady state should be investigated at the next stage. To carry out this study more detailed information would be required concerning the way in which the bus station will be used.

During the detailed design stage it may be necessary to carry out an additional study of the wind effects in the two following cases: firstly in the bus occupied areas where the wind will determine the ambient pollutant levels, and secondly on the external doors where the local wind pressures developed will influence the ingress of bus exhaust fumes.

4.2 The Wind Tunnel Tests

These tests were carried out on a 1:400 scale model (Figure 6) of the passenger interchange and its surrounding passenger interchange by T. W. Everett and T. V. Lawson using the environmental wind tunnel in the Department of Aeronatural Engineering at the University of Bristol. This tunnel can be used to model:

a) Variation of mean windspeed with height
b) Variation of turbulence with height
c) Spectrum of turbulence at all heights.

This paper is not intended to be a discussion of the way wind tunnels can be used to model atmospheric winds, so if more information should be required references [12-14] contain the theoretical basis for the wind tunnel studies.

4.2.1 The Investigation

The objective of the study was to provide data on the air change rates in the concourse and bus stand area as a function of wind speed and direction. To do this it was first necessary to obtain surface pressure coefficients on both the open sides of the bus stand area and all surfaces of the urban concourse. The measurement of pressures on open areas is difficult so artificial walls were introduced, at the sides of the bus stands. These were removed for the concourse ventilation prediction. The measured pressure coefficients were then used as input to a computer program (not the one described here) along with leakage areas to predict ventilation flow rates.

Such tests only provide data for particular combination of wind speed and directions. To be of value in determining the probability of obtaining satisfactory ventilation rates for the purpose of pollutant removal, it is necessary to relate the results to local weather data. It is then possible to determine the frequency of occurrence of specified air charge rates.

In the present case the only meteorological data available was for Santander, and this was restricted to 0700 and 1800 hours. All analysis was therefore based on these data, which comprised both wind speeds and direction. Should data for Bilbao town centre ever become available then it would be simple to repeat the analysis with that data.

4.2.2 Results

The results of the analysis were used to calculate the percentage of time for which a stated volume flow rate would be exceeded in

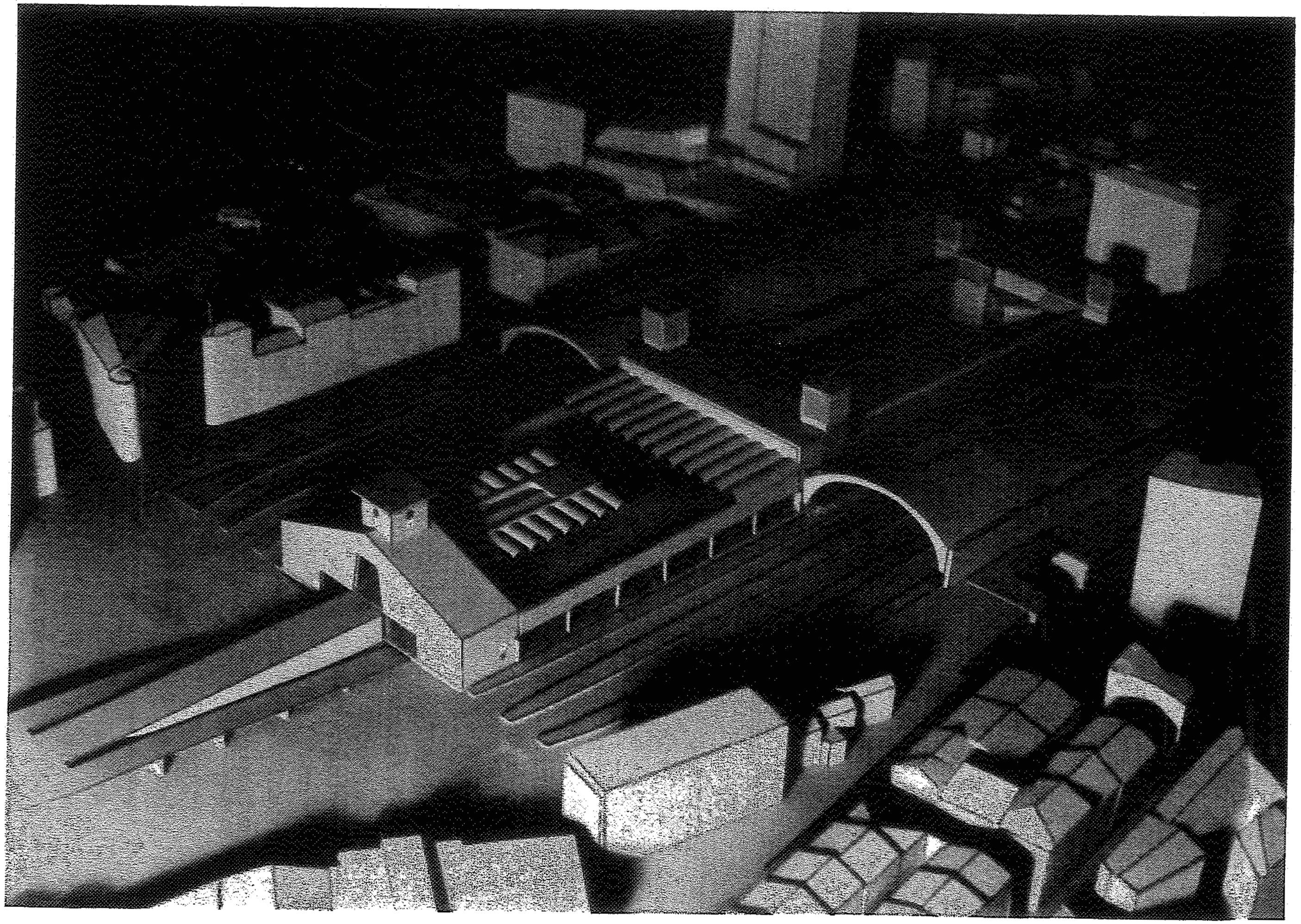


Figure 6 The wind tunnel model

both the bus stand and concourse areas at 0700 and 1800 hrs. In the case of the former, two example were considered:

All external doors open (12 bays each of three $4m^2$ doors).

A 'restricted opening' with a single $4m^2$ door open on the existing station side and 4 bays of three $4m^2$ doors on the other.

Detailed results cannot be of any general interest so it is only pertinent to quote the general conclusions which were:

a) Bus Areas

A ventilation rate of three air changes per hour in the bus areas would be exceeded 96.3% of the time at 07:00 hours and 96.7% of the time at 18:00 hours. There is very little variation of these average figures through the year. 6 air changes would be exceeded 92% of the time and 1 air change 99% of the time.

These figures indicate that natural ventilation is an adequate method of ventilating the bus areas of the suburban bus station. On calm days when the required air change rates will not be achieved, there will be significantly less distribution and mixing of bus exhaust fumes; these will tend to rise up out of the occupied space and so should not pose a threat to safety. In addition, at these times, fumes at low level will be more concentrated and so will be avoided naturally due to their unpleasantness.

The fact that polluted air may re-enter the bus area at some points has been taken into account in assuming a ventilation efficiency of 50% in calculating the required air change rates.

b) Concourse Areas

With all doors open all of the time and no pressurisation, a ventilation rate of three air changes per hour in the concourse area is exceeded 61% of the time and a rate of one air change per hour is exceeded 87% of the time. With restricted openings these figures reduce to about 9% and 49% respectively.

The figures are theoretical and the following points need to be considered before drawing any conclusions:

It is assumed that in each case doors will be open all the time. As already discussed all 12 stands will only be full for 5 minutes in the peak hour and even then the single entry and two exit doors will not be open together. The case with all doors open simply serves to prove therefore that natural ventilation of the concourse area is not possible.

Table 9: Example of result from wind tunnel tests

Concourse air change rates

MONTH	TOTAL VOLUME AIR CHANGE RATE EXCEEDED hr^{-1}									
	1	2	3	4	5	6	7	8	9	10
JAN	88.5	76.0	64.8	55.2	47.1	40.3	34.6	29.8	25.7	22.3
	53.0	25.6	12.7	6.4	3.3	1.7	0.9	0.5	0.3	0.1
FEB	91.4	80.8	70.1	60.2	51.3	43.6	37.0	31.4	26.7	22.7
	57.7	26.8	11.6	5.0	2.1	0.9	0.4	0.2	0.1	-
MAR	88.3	76.5	65.8	56.3	48.1	41.0	34.9	29.8	25.4	21.7
	53.2	26.1	12.6	6.1	3.0	1.5	0.8	0.4	0.2	0.1
APR	87.0	74.9	64.1	54.8	46.9	40.1	34.5	29.6	25.6	22.1
	51.1	24.8	12.2	6.2	3.3	1.8	1.0	0.6	0.3	0.2
MAY	84.3	68.3	54.8	44.1	35.6	29.0	23.8	19.5	16.1	13.3
	41.5	14.5	5.0	1.8	0.7	0.3	0.1	-	-	-
JUNE	81.6	62.7	47.4	35.9	27.5	21.3	16.7	13.1	10.4	8.3
	35.0	10.0	2.8	0.8	0.3	0.1	-	-	-	-
JULY	81.9	63.2	47.6	35.6	26.6	20.0	15.2	11.6	8.9	6.9
	35.2	9.7	2.4	0.6	0.1	-	-	-	-	-
AUG	85.8	68.6	52.9	40.1	30.1	22.4	16.7	12.5	9.4	7.1
	40.3	10.5	2.3	0.5	0.1	-	-	-	-	-
SEPT	85.3	70.1	56.7	45.5	36.5	29.3	23.7	19.2	15.6	12.7
	46.6	18.3	6.9	2.7	1.1	0.5	0.2	0.1	-	-
OCT	88.8	76.5	64.6	53.9	44.9	37.5	31.6	26.9	22.9	19.6
	52.0	21.7	9.4	4.3	2.0	0.9	0.4	0.2	0.1	0.1
NOV	89.9	79.0	68.6	59.2	50.9	43.7	37.6	32.4	27.9	24.1
	57.2	28.5	13.8	6.6	3.1	1.5	0.7	0.3	0.2	0.1
DEC	89.3	78.6	68.7	59.8	52.0	45.2	39.4	34.5	30.2	26.5
	57.3	30.3	16.2	8.9	5.1	2.9	1.7	1.0	0.6	0.4

Note: Upper set of figures for each month are for all doors open and the lower for restricted opening.

The 'restricted openings' case is however, a little more realistic but even this assumes that doors are open continuously in any one hour. In practice doors will be opening and closing on the windward and leeward sides and there will be significant periods in any one hour when all the doors are closed.

No allowance has been made for the shielding effect of the buses.

No account has been taken of the modification to airflow rates caused by pressurising the concourse. This will only have an effect at low external windspeeds (although a velocity pressure of 50Pa corresponds to a wind velocity of 9.12m/s).

Taking all these factors into account, it would be safe to assume that three air changes will very seldom be exceeded and one air change will only be exceeded for about 10% of the time.

Thus mechanical ventilation again is predicted as essential if a satisfactory environment is to be generated within the waiting area. It is also of interest that the very simple calculation shown in Section 4.1.1 did not lead to a conclusion different from that of the wind tunnel tests. The advantage of these tests was the detailed information provided, such as the frequency of occurrence of different airchange rates, an example of which is given in Table 9.

5. PROGRAM VENT

This program is intended to predict air movement through both purpose built openings and fabric imperfections between spaces or rooms. The driving force for this can be a combination of:

a) Wind pressure.
b) Internal/external temperature difference (stack effect).
c) Temperature difference between rooms.
d) Mechanical plant.

The output from the program comprises:

a) Summary of the input data.

b) A summary of all air-flows from outside to each room, the corresponding airchange rate, and heat gain. In addition the continuity error is given. The program works by satisfying the continuity equation for each room (mass flow in = mass flow out). An iterative solution technique is used, so there will be an error in the flow balance. This is displayed so that the overall accuracy of the prediction can be assessed.

c) Room by room details of the air-flow through each ventilation opening to the outside, and between rooms.

d) A trace of flows or contaminants. It is assumed that the level of a pollutant is held at 100% in the "source room". The level in adjacent rooms depends upon dilution by 'pure' outside air and pure or slightly contaminated inside air. The percentage level of the contaminant (relative to the source room, 100% level) is presented, with each room taken as the source in turn.

5.1 Standard Data

Vent has a small data base of leakage characteristics. This is in the process of development. The current content are given in Table 10.

Table 10: Standard Leakage Data

Description	D	k	n	Code
Own data				0
Window, pivoted, closed	Crack length	$2.1\text{x}10^{-4}$	0.63	1
Window, pivoted, weatherstrip closed	Crack length	$0.3\text{x}10^{-4}$	0.63	2
Window, sliding, closed	Crack length	$0.8\text{x}10^{-4}$	0.63	3
Door, single, stairwell, closed	No. of doors	$1.5\text{x}10^{-2}$	0.5	4
Lift door, closed	No. of doors	$4.0\text{x}10^{-2}$	0.5	5
External door with sill, closed	Crack length	$1.6\text{x}10^{-3}$	0.5	6
Standard fire stop door	Crack length	$2.6\text{x}10^{-3}$	0.5	7
Lift door with 5mm crack	Crack length	$4.2\text{x}10^{-3}$	0.5	8
216mm plain brick	Surface area	$4.6\text{x}10^{-5}$	0.87	9
216mm brick plastered	Surface area	$4.0\text{x}20^{-7}$	0.87	10
330mm plain brick	Surface area	$4.1\text{x}10^{-5}$	0.87	11
330mm brick plastered	Surface area	$4.0\text{x}10^{-7}$	0.87	12
External curtain wall	Surface area	$3.0\text{x}10^{-4}$	0.5	13
Floors	Surface area	$2.0\text{x}10^{-4}$	0.5	14
Hole or orifice	Surface area	0.83	0.5	15

5.2 Vent Algorithm

This section describes what is done by program VENT, using a combination of text and flow charts.

The VENT flow chart is given in Figure 7 which contains the subroutines, PCOR, ACALC and FOLLOW; their functions are described in the following sections.

5.2.1 Subroutine PCOR

This is used to calculate corrected external and internal pressures for use in the calculation of air-flow rates and internal pressure. External pressures are corrected for position and stack effect, whilst internal corrections are only required to take account of temperature differences between rooms. The corrections are:

a) External Pressure at any path:

$$PEX = \frac{1}{2} C_p \rho_e V_w{}^2 F - H_D g \rho_e + H_{Fi} g \rho_i \qquad (2)$$

b) Internal correction

$$COR = g(H_{fi} \rho_i - H_{Fj} \rho_j) \qquad (3)$$

where ρ_e = external air density (kg/m³)

V_w = wind speed (m/s)

F = location correction factor (m/s)

C_p = pressure coefficient (m/s)

H_D = height of leakage path above datum (m)

g = acceleration due to gravity (m)

H_{Fi} = height of opening above floor of Room i (m)

ρ_i = density of air in Room i (kg/m³)

and suffix j refers to conditions in adjacent room number j.

The internal correction (COR) is subtracted from the difference in pressure between two rooms. The corrected external pressure (PEX) replaces the external pressure in all flow calculations.

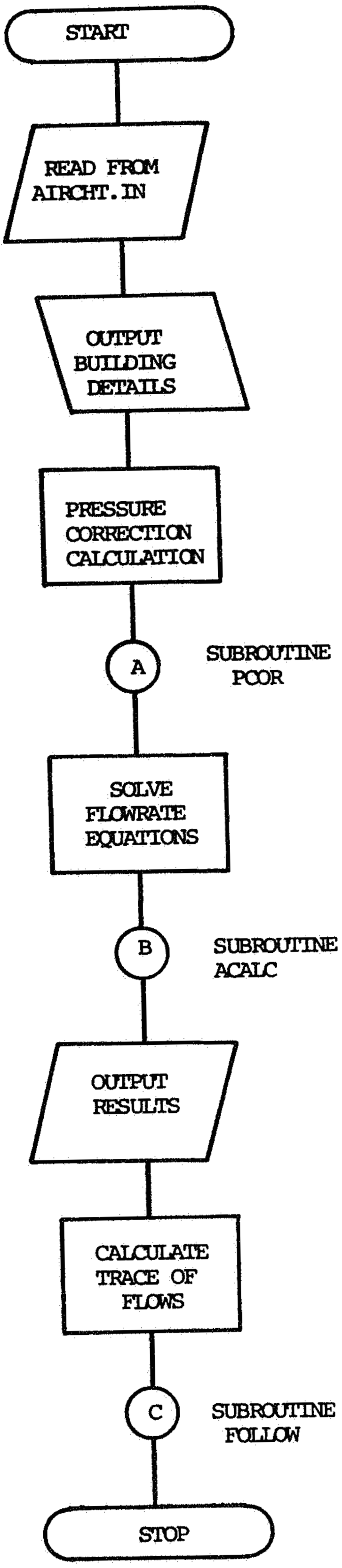
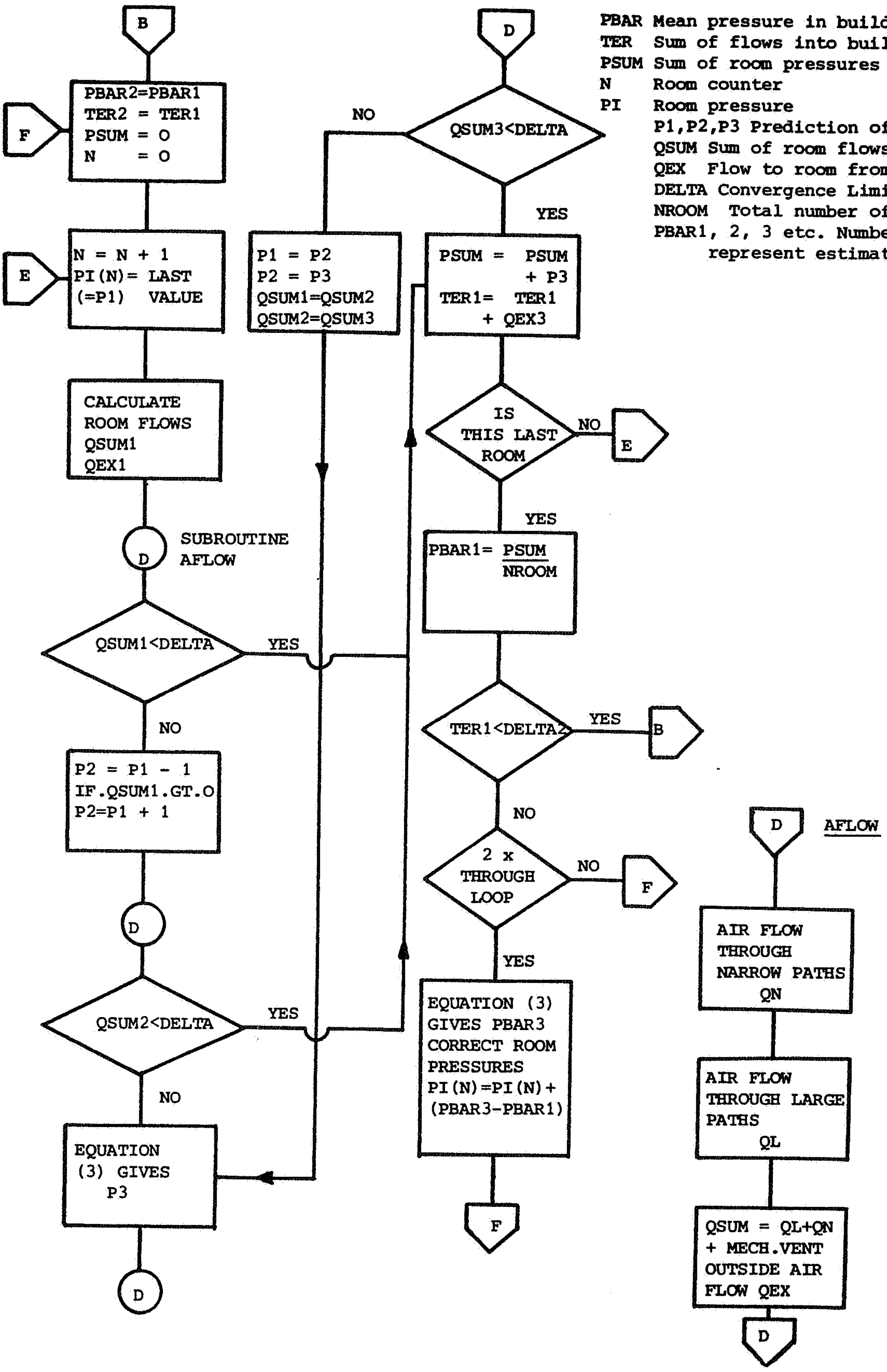


Figure 7 Vent flow chart



NOMENCLATURE

PBAR	Mean pressure in building
TER	Sum of flows into building
PSUM	Sum of room pressures
N	Room counter
PI	Room pressure
P1,P2,P3	Prediction of PI
QSUM	Sum of room flows
QEX	Flow to room from outside
DELTA	Convergence Limit
NROOM	Total number of rooms
PBAR1, 2, 3 etc.	Numbers represent estimate number

Figure 8 Acalc flow chart

5.2.2 Subroutine ACALC

This is the main calculation routine. The object is to satisfy the continuity equation for each room, and the whole building. In general the air flow equations are non-linear, so it is necessary to employ an iterative technique. The method employed is a numerical form of the well known Newton-Raphson technique. This approach is used so that almost any flow equation can be incorporated into VENT. An example of what might be included is given in Section 5.2.4.

Taking the room flow balance as an example:

a) An estimate is made of the internal pressure (P1), and the sum of all flows from outside and adjacent rooms calculated, this should be zero, but unless the estimate is good, will have some value QSUM1 (calculated by Subroutine AFLOW which determines air flow from pressure drop).

b) Using a second estimate, P2, calculate QSUM2.

c) A better estimate of the room pressure is then obtained from:

$$P3 = P2 + QSUM2 \times (P2-P1)/(QSUM1-QSUM2) \qquad (4)$$

Calculate:

QSUM3 = flow sum at room pressure P3; check if near to zero and if not:

d) P1 = P2
P2 = P3
QSUM1 = QSUM2
QSUM2 = QSUM3
Return to (c) - and continue.

The process is applied to the whole building as well as each room, with the mean building pressure replacing room pressure in Equation (3). Figure 8 presents the flow chart for ACALC. Room convergence limits are based on the maximum flow from any single room opening and building convergence is related to the maximum flow through any single external opening.

Additional checks are made to ensure that QSUM1 is not equal to QSUM2, if this occurs then convergence is assumed - although a warning message is written to the terminal or log file. Experience has shown that such an event only occurs when close to a converged solution.

5.2.3 Subroutine FOLLOW

This subroutine is used to trace the passage of a contaminant from a source room, through each room in the building. It is assumed that the level in the source room is constant at 100%, the dilution in other rooms can then be calculated by solving the set of equations:

$$L_i Q_i - \sum_{j=i}^{j=N_r} L_j Q'_j = 0 \qquad (5)$$

where L_i is the level of the contaminant in Room (%)
Q_i is the air flow rate <u>leaving</u> Room i (m^3/s)
L_j is the level of the contaminant in Room j (%)
Q'_j is the flow of air <u>from</u> Room j <u>to</u> Room i (m^3/s)
N_r is the number of rooms minus 1 (no solution is required for the source room).

Each room is treated as a source room in turn (unless there is no flow to adjacent rooms), so Equations (5) are solved N_r times. Gaussian elimination, with partial pivoting is used. Matrix inversion - based methods are not suitable because the equation set changes as the source room is changed.

5.2.4 Example of an analytical flow solution

The example is the calculation of flow through a large opening. Consider an opening of height H, with external conditions given the suffix 0 and internal i. then:

The pressure at any height (y) is:

$$\text{Outside} \quad P_o - y\,g\,\rho_o \qquad (7)$$

$$\text{Inside} \quad P_i - y\,g\,\rho_i$$

Where P is the presure at y = o
g is the gravitational constant
ρ is the density of air, assumed here to be independent of height.

The point where these are equal, the neutral plane (y = z) defines a boundary above which (if the inside is hotter than the outside) air flows out from the building, and below which there is a cold inflow.

$$Z = \frac{P_o - P_i}{g\,(\rho_o - \rho_i)} \qquad (8)$$

The flow into the building per unit width of opening is (Q_i):

$$Q_i = W \int_0^z C_D \left\{ P_o - P_i - y\,g\,(\rho_o - \rho_i \right\}^{\frac{1}{2}} dy \qquad (9)$$

or

$$Q_i = \frac{2}{3} W C_D \,(P_o - P_i)^{3/2} / (\rho_o - \rho_i) g \qquad (10)$$

where:

W is the width of the opening

C_D is the discharge coefficient

The outflow (is obtained by integrating between the neutral plane and the top of the opening H, giving:

$$Q_i = \frac{2}{3} W C_D \,(P_i - P_o + H_g(\rho_o - \rho_i))^{3/2} / (\rho_o - \rho_i) g \qquad (11)$$

6. CONCLUSIONS

This paper has attempted to describe the basis of the design for the ventilation of the bus station in fairly general terms, in particular to demonstrate how the work of the Air Infiltration and Ventilation Centre is used in industry. The paper does not contain a lengthy discussion of computer predictions because the inclusion of large numbers of calculations are of little value to those not directly involved with the design. More detailed information is available and can be supplied on request, by the authors.

The design of the ventilation system does, of course, not stop with the calculation of the required flow rates. It is necessary to size plant, locate the fresh air inlets in positions where there is the best chance of taking in the least polluted air, and in this example, assessing the time required to achieve full pressurization after the doors are closed. At present the project is still in the form of a proposal so no detailed design has been done. It is possible that the situation may have changed by the time of the conference.

7. ACKNOWLEDGEMENTS

The design of a building is a team effort, and the authors wish to acknowledge the contributions of their colleagues in the Ove Arup Partnership and in particular Fiona Cousins.

8. REFERENCES

[1] Fanger P.O. Thermal Comfort. Danish Technical Press. Copenhagen 1970.

[2] Holmes M.J. Design for Ventilation. Proceedings 6th AIC Conference. Ventilation strategies and measurement techniques. 16-19 September 1985.

[3] Health and Safety Executive. Occupational Exposure limits. 1986.

[4] Bendelius A. Design criteria for Vehicular road tunnels. Ashrae Journal. June 1985.

[5] Messresultate des Nationalen Beobachtungsnetzes fur Luftfremdstoffe (NABEL). Schritenreibe Umweltschutz. Nr 42. Herausgegeben vom Bundesamt fur Umweltschutz, Bern. September 1985.

[6] Private communications. Warren Springs Laboratory (UK). Transport and Roads Research Laboratory (UK).
Health and Safety Executive (UK).

[7] London Transport. Exhaust Gas Analysis of Leyland 0600 Engine.

[8] Private communication from Motor Industries Research Association. Analysis of BOSCH engine exhaust gases.

[9] Haerter AA. Fresh Air rates for road tunnels. AVVT. 1973.

[10] CIBSE Guide Book B. Section B2, Chartered Instituion of Building Services Engineers. 1986.

[11] CIBSE Guide Book A, Section 14, Chartered Institution of Building Services Engineers. 1986.

[12] E.S.D.U. "Strong Winds in the Atmospheric Boundary Layer, Part 1 Mean Hourly Speeds" ESDU Data Item 82026 Amend. A Dec. 1982. (Obtainable from ESDU International Ltd., 251-259 Regent Street, London W1R 7AD).

[13] COOK N.J. "Wind Tunnel Simulation of the Adiabatic Atmospheric Boundary Layer of Roughness, Barrier and Mixing Device Methods" Journal of Indust Aerodynamics Vol 3 Nos 2/3 July 1978.

[14] E.S.D.U. Characteristics of Atmospheric Turbulence near the Ground Part 11 : Single Point Data for Strong Winds (Neutral Atmosphere)" EDU Data Item 74031 Amend A March 1975.